Possibility of observing neutron spin precession in an antiferromagnet

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It is shown that even in the case of antiferromagnetic ordering of the lattice spins (and consequently at zero average magnetic field of the target) it is possible to observe neutron-spin precession and to obtain polarized neutron beams.

It is well known[1] that when neutrons pass through a ferromagnet their spin precesses in the macroscopic magnetic field produced by the polarized electrons. If the electron-polarization vector averaged over the target is equal to zero, then the macroscopic magnetic field is equal to zero and there is no spin precession. This means that when neutrons pass through an antiferromagnet there is no neutron spin precession.

Similarly, nuclear precession of the neutron spin, which was predicted by Podgoretskiĭ and the author[2] (and recently observed experimentally by Abragam's group[3]) does not exist if the spins of the nuclei are antiferromagnetically ordered,[1)] owing to the vanishing of the average effective quasimagnetic nuclear field.

We shall show below that in spite of the foregoing it is possible to observe magnetic (nuclear) precession of the neutron spin even in the case of antiferromagnetic ordering, provided that the neutrons are diffracted in the target.

Let us investigate further, for the sake of argument, the case of diffraction in a plane-parallel plate of a collinear antiferromagnet, of thickness l, with electron (nuclear) spins directed perpendicular to the surface of the plate. We choose the z axis of the coordinate system, which is perpendicular to the surface of the plate, as the quantization axis. In this case the state $\Psi_+(\Psi_-)$ of a neutron with a spin parallel (antiparallel) to the z axis is stationary and the diffraction of such neutrons can be regarded independently. As a consequence we can use the well-known theory of dynamic diffraction in an unpolarized crystal[5,6] to analyze the diffraction process. According to this theory, in the case of symmetrical Laue diffraction by a system of planes defined by the reciprocal-lattice vector τ, the wave function describing the neutrons passing through the plate is given by

$$\Psi_\pm = \frac{(2\epsilon_2^\pm - g_\pm(0))\, e^{ik_0\epsilon_1^\pm \frac{l}{\gamma}} - (2\epsilon_1^\pm - g_\pm(0))\, e^{ik_0\epsilon_2^\pm \frac{l}{\gamma}}}{2(\epsilon_2^\pm - \epsilon_1^\pm)}\, e^{i\mathbf{k}_0\mathbf{r}}$$

$$- \frac{g_\pm(\vec{\tau})}{2(\epsilon_2^\pm - \epsilon_1^\pm)}\left[e^{ik_0\epsilon_1^\pm \frac{l}{\gamma}} - e^{ik_0\epsilon_2^\pm \frac{l}{\gamma}}\right] e^{i(\mathbf{k}_0 + 2\pi\vec{\tau})\mathbf{r}}, \qquad (1)$$

$$\epsilon_1^\pm = \frac{1}{4}[2g_\pm(0) - a] + \frac{1}{4}\sqrt{a^2 + 4g_\pm(\vec{\tau})g_\pm(-\vec{\tau})},$$

$$\epsilon_2^\pm = \frac{1}{4}[2g_\pm(0) - a] - \frac{1}{4}\sqrt{a^2 + 4g_\pm(\vec{\tau})g_\pm(-\vec{\tau})},$$

$\gamma = \mathbf{k}_0 \cdot \mathbf{n}/k_0$, $\mathbf{n}$ is the normal to the surface of the plate, $\mathbf{k}_0$ is the wave vector of the incident particles,

$$a = \frac{2\pi\vec{\tau}(2\pi\vec{\tau} + 2\mathbf{k}_0)}{k_0^2}, \quad g_\pm(\vec{\tau}) = \frac{4\pi}{\Omega k_0^2}\sum_j f_{j\pm}(\vec{\tau})e^{-i2\pi\tau\rho_j},$$

Ω is the volume of the unit cell, ρ_j is the coordinate of the j center in the cell, $f_{j\pm}(\tau)$ is the amplitude of the elastic coherent scattering of the neutrons, with spin parallel (antiparallel) to the z axis at the center, contained in the unit cell (the contribution to the total cross section from the elastic coherent scattering is excluded from the imaginary part of f_j). In the case of diffraction in a nuclear antiferromagnetic, for example, we have $f_{j\pm}(\tau) = (\alpha \pm \beta p_{jz})\exp[-w(\tau)]$, where the polarization of the nuclei is $p_{jz} = \pm|p|$ and $\exp[-w(\tau)]$ is the Debye-Waller factor.

Using (1) we can find the polarization vector of the neutrons behind the plate at an arbitrary initial direction of their spin.

If there is no diffraction ($\alpha \gg g$), then it follows from

(1) that the polarization vector of the neutrons behind the plate have the following transverse components (the polarization vector of the neutrons in front of the plate is directed along the x axis):

$$P_x = \cos\left\{k_0 \frac{\mathrm{Re}(g_+(0) - g_-(0))}{2} \frac{l}{\gamma}\right\} \exp\left\{-\frac{k_0 \mathrm{Im}(g_+(0) + g_-(0))}{2} \frac{l}{\gamma}\right\} \tag{2}$$

P_y is obtained from P_x by replacing cos by $-\sin$.

In the presence of diffraction, the polarization vector of the neutrons moving in the direction $(\mathbf{k}_0 + 2\pi\boldsymbol{\tau})$ has the following components (for simplicity we assume exact fulfillment of the Bragg conditions $(\alpha = 0)$):

$$\begin{aligned} P_x = \frac{1}{4}\Big\{ & \cos\left[k_0 \mathrm{Re}(\epsilon_1^+ - \epsilon_1^-)\frac{l}{\gamma}\right]\exp\left[-k_0 \mathrm{Im}(\epsilon_1^+ + \epsilon_1^-)\frac{l}{\gamma}\right] \\ & - \cos\left[k_0 \mathrm{Re}(\epsilon_1^+ - \epsilon_2^-)\frac{l}{\gamma}\right]\exp\left[-k_0 \mathrm{Im}(\epsilon_1^+ + \epsilon_2^-)\frac{l}{\gamma}\right] - \cos\left[k_0 \mathrm{Re}(\epsilon_2^+ - \epsilon_1^-)\frac{l}{\gamma}\right] \\ & \times \exp\left[-k_0 \mathrm{Im}(\epsilon_2^+ + \epsilon_1^-)\frac{l}{\gamma}\right] + \cos\left[k_0 \mathrm{Re}(\epsilon_2^+ - \epsilon_2^-)\frac{l}{\gamma}\right]\exp\left[-k_0 \mathrm{Im}(\epsilon_2^+ + \epsilon_2^-)\frac{l}{\gamma}\right]\Big\} \end{aligned} \tag{3}$$

P_y is obtained from P_x by replacing cos by $-\sin$.

We proceed to analyze the obtained relations.

We note first that in the absence of diffraction, according to (2), the neutrons precess only at a nonzero difference $g_+(0) - g_-(0)$. This takes place only when the spins of the target are polarized predominantly in one direction.[2] A different situation arises in the presence of diffraction. In this case, even in an antiferromagnet, the structure amplitude $g_\pm(\tau)$ depends on the orientation of the incident-particle spin (see[8], Secs. 26 and 27). Consequently, the differences of the values $\epsilon_{1,2}^{\pm}$ of interest to us are determined for an antiferromagnet by the following equations $(\alpha = 0)$:

$$\epsilon_1^+ - \epsilon_1^- = -(\epsilon_2^+ - \epsilon_2^-) = \frac{g_+(\vec{\tau}) - g_-(\vec{\tau})}{2}; \quad \epsilon_1^+ - \epsilon_2^- = -(\epsilon_2^+ - \epsilon_1^-) = \frac{g_+(\vec{\tau}) + g_-(\vec{\tau})}{2}. \tag{4}$$

According to (3) and (4), the neutron spin can precess under diffraction conditions at four frequencies (two frequencies with different absolute values) even in an antiferromagnet (just as in a ferromagnet[7]).

We discuss now diffraction in the Bragg case. Since the theory describing the diffraction of each spin component fully coincides in form with the dynamic theory of diffraction in an unpolarized crystal, it follows that one can write down immediately the diffraction-reflection coefficient for each spin component of the neutron wave (see, e.g.,[8]). These coefficients depend on the values $\epsilon_{1,2}$, which in our case are different for different directions of the incident-neutron spin. As a consequence, the diffraction-reflection coefficients will have maxima at different particle-incidence angles. Consequently, just as in diffraction reflection from a ferromagnet, it is possible to produce in this case reflection of only one component of the incident-beam spin, and thus obtain a polarized neutron beam.

[1)]Antiferromagnetic ordering of nuclear spins was observed experimentally by Abragam's group (see[4] and the references cited therein).

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